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Vulnerability of Wires and Cables

by
Thomas W. Ipson
Rodney F. Recht
William A. Schmeling
Denver Research Institute
University of Denver
for the
Systems Development Department

JUNE 1977

Naval Weapons Center
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FOREWORD

The Joint Technical Coordinating Group for Munitions Effectiveness (JTCG/ME) tasked the Surface Target Survivability/Vulnerability Program (STS/VP) to produce survivability/vulnerability data for surface targets. These vulnerability values are subsequently utilized by the Joint Munitions Effectiveness Manual for Air-to-Surface (JMEM/AS) and the Joint Munitions Effectiveness Manual for Surface-to-Surface (JMEM/SS) for weapons effectiveness calculations versus these surface targets. This report partially fulfills the vulnerability requirements with which the JMEM/AS and the JMEM/SS has tasked the STS/VP.

The work on this task was accomplished by the Denver Research Institute under Contract No. N00123-76-C-0166 and N00123-72-C-0267 for the Naval Weapons Center. Funding was provided by the JTCG/ME through the Army Materiel Systems Analysis Activity as executive agency on MIPR RA 30-73.

This report has been reviewed for technical accuracy by M. H. Keith.

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20. Abstract

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VULNERABILITY OF WIRES AND CABLES

Contract Number N00123-72-C-0267

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Denver Research Institute
of the
University of Denver

APPROVED BY:

Rex E. Paulsen
Rex E. Paulsen, Head
Mechanical Sciences Division

PREPARED BY:

Tom W. Ipson
Tom W. Ipson
Research Engineer

Rodney F. Recht
Rodney F. Recht
Senior Research Engineer

William A. Schmeling
William A. Schmeling
Research Engineer

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INTRODUCTION

The objective of this research effort was to produce experimentally verified models capable of predicting the vulnerabilities of single wires, wire bundles, cables, and coaxial cables as functions of the masses and velocities of ballistic fragments and of attack aspect. Ballistic experiments were conducted with various size fragments against solid conductor wires, stranded conductor wires, coaxial cable, and a large multiple conductor cable. Equations which predict the breaking velocity in terms of fragment mass, and models for determining vulnerable areas, were developed for wires and coaxial cable. Models, based upon these single conductor equations, were developed for determining the vulnerability of multiple conductor cables.

Reported herein is a description of the experimental procedure employed during the firing program, a presentation of the experimental results, development of prediction models, and a discussion of their use as applied to multiple conductor cables. An example is presented which illustrates how the models are used to evaluate vulnerability of multiple conductor cables.

EXPERIMENTAL PROGRAM

PROCEDURE

During the experimental firing program, single conductor wires (both solid and stranded conductor), coaxial cable, and a multiple conductor cable were investigated. The breaking velocity, V_{bw}, (that velocity for which there is a 0.5 probability of cutting the wire in two) was determined for several sizes of soft copper solid conductor wire and various size fragments. The breaking velocity of one size of stranded soft copper single conductor wire was determined for comparison purposes. RG-8/U coaxial cable was impacted by 6-grain and 17-grain fragments: breaking velocities were determined for the center conductor. Shorting of the center conductor to the shielding was also noted. Seventeen grain fragments were fired at a large (0.85-inch overall diameter), 25 conductor cable. In these tests, impact direction (with respect to the conductor orientation within the cable) and the number and type of wires cut or shorted were noted.

The test fragments used in this study were 3.75 and 6 grain mild steel cubes and the 17-grain (.22 caliber) Watertown Arsenal Laboratories developed Fragment Simulating Projectile (FSP). These fragments were fired from a .22 caliber powder gun and from a Crosman Model 140 air rifle. The cubical fragments were fired from the air rifle utilizing lightweight balsa wood sabots. The impact velocity (V) of the fragments was determined by means of photo cells or etched copper make switches which were used to trigger a chronograph. The photocell technique was used with the lighter cubical fragments since passage through a make switch could alter velocity significantly.

All wire and cable specimens were firmly clamped at the ends. The standard distance between the fixed ends was 6 inches. Limited testing was conducted with 3 and 12-inch spans between fixed ends to study the possible effects of wire length.

The breaking velocity for wires (V_{bw}) was determined in a manner similar to that used to determine ballistic limit velocities for plates. Firings were conducted in a velocity zone which produced both breaks and non-breaks of the wire. Firings were continued until three breaks and three non-breaks were obtained within a velocity spread of 100 ft/sec. These six velocities were then averaged to obtain the (V_{bw}) value. Only hits where the presented area of the test fragment fully covered the wire were considered; results for nicks or partial hits were ignored. Figure 1 illustrates typical data obtained for solid, soft copper conductor wire. The data presented in this figure concerns the behavior of Nos. 6, 8, and 10 gage (AWG) wires when impacted with the 17-grain fragment simulator. The data are plotted to illustrate response as a function of impact velocity. The data for Nos. 8 and 10 gage wire pertain to a 6-inch length between fixed ends. The data for the No. 6 gage wire concern 3, 6, and 12-inch lengths between clamped ends.

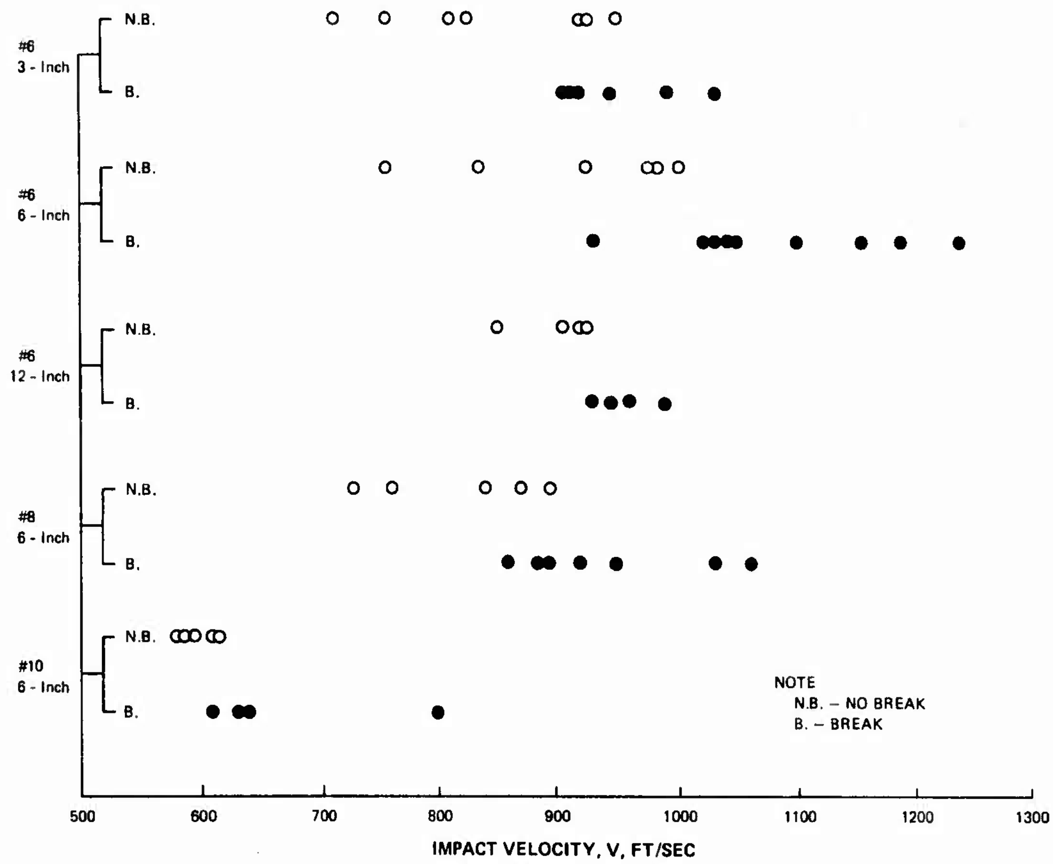

FIG. 1. Breaking Velocity Data for 17-Grain Fragment Impacting Various Sizes of Solid Conductor, Soft Copper Wire at 0° Obliquity.

In the case of coaxial cable tests, two malfunction criteria were observed. Tests were conducted to establish the breaking velocity for the center conductor and a velocity related to shorting of the center conductor and the shielding (by means of the fragment being imbedded in the cable). The 17-grain fragment tests involving the RG 8/U coaxial cable produced a breaking velocity (center conductor) of 800 ft/sec. At impact velocities above 650 ft/sec shorting of the center conductor to the shielding occasionally occurred. Thus, the breaking velocity for the 17-grain fragment represents a slightly conservative estimate of the velocity required to cause a malfunction. During later model development, shorting was ignored (conservatively) since it was not consistent. In the case of the smaller 6-grain cubical fragment, impact velocities which caused shorting were very near those which caused severance of the center conductor. In this case, both criteria (shorting or breaking of the center conductor) were used to establish a value for the breaking velocity.

RESULTS

Table 1 presents the results of the firing program for single conductor wires and coaxial cable, in terms of the breaking velocity V_{bw}. The tests of the three different lengths of No. 6 gage wire (.162 inch dia.) with the 17-grain fragment produced similar results. It was anticipated that the shorter wire might produce a lower (V_{bw}) value because of the reflection of strain waves from the fixed ends. However, this test series indicates that breaking time is short enough that the wire length can be ignored.

TABLE 1. Results of Firing Program.

Breaking velocities (V_{bw}) determined for single conductor wires and a coaxial cable

Type of Wire	Frag. Wt. M_p, grains	Wire Dia. d_w - in.	Length Between Fixed Ends-in.	Breaking Vel. V_{bw} - ft/sec
Solid, soft copper.....	17	.040	6	435
	17	.102	6	615
	17	.128	6	875
	17	.162	6	1005
	17	.162	3	930
	17	.162	12	930
	6	.102	6	845
Stranded, soft copper.....	17	.051	6	330
	3.75	.051	6	500
RG 8/U Coaxial cable.....	17	.072	6	800
	6	.072	6	1000

A limited test series was performed, using the 17-grain fragment, to examine the response of the multiconductor cable to ballistic impact.

This test series was designed to develop modelling insights and provide data necessary to develop a useful vulnerability model. Verification and/or improvement of this tentative model will require an extensive firing program considering the multiplicity of attack aspects, fragment sizes, and impact velocities of interest. Figure 2 shows a cross section of the cable tested. This cable is 25 conductor TV camera cable (TV 25 TN) made by the Boston Insulated Wire and Cable Co. A 1/8-inch rubber jacket covers the cable. A steel braided shield lies beneath the jacket. On Fig. 2, the wire types are assigned a number (encircled) for reference in describing the results of the firing program. These numbers do not refer to gage sizes (wire diameters, d_w, are shown but are for reference only). Note that the number 3 and number 4 wires have the same diameter conductor but different insulation thickness. Directional arrows are used to reference the direction (with respect to the wire orientation) of impact trajectory. Table 2 lists the results of the firings at this cable. Shown are the impact velocity, the direction of impact, and the number and type of wires cut or functionally damaged by the fragment. The majority of these tests were fired from the 0^{o} direction into the group of four large wires. Essential information concerning the behavior of single conductor wires when enclosed within a cable was obtained.

Results of this experimental firing program provide a limited basis for the development of prediction models useful for estimating the vulnerability of single conductor wires and cables and multiple conductor cables. In the next two sections, such models are developed.

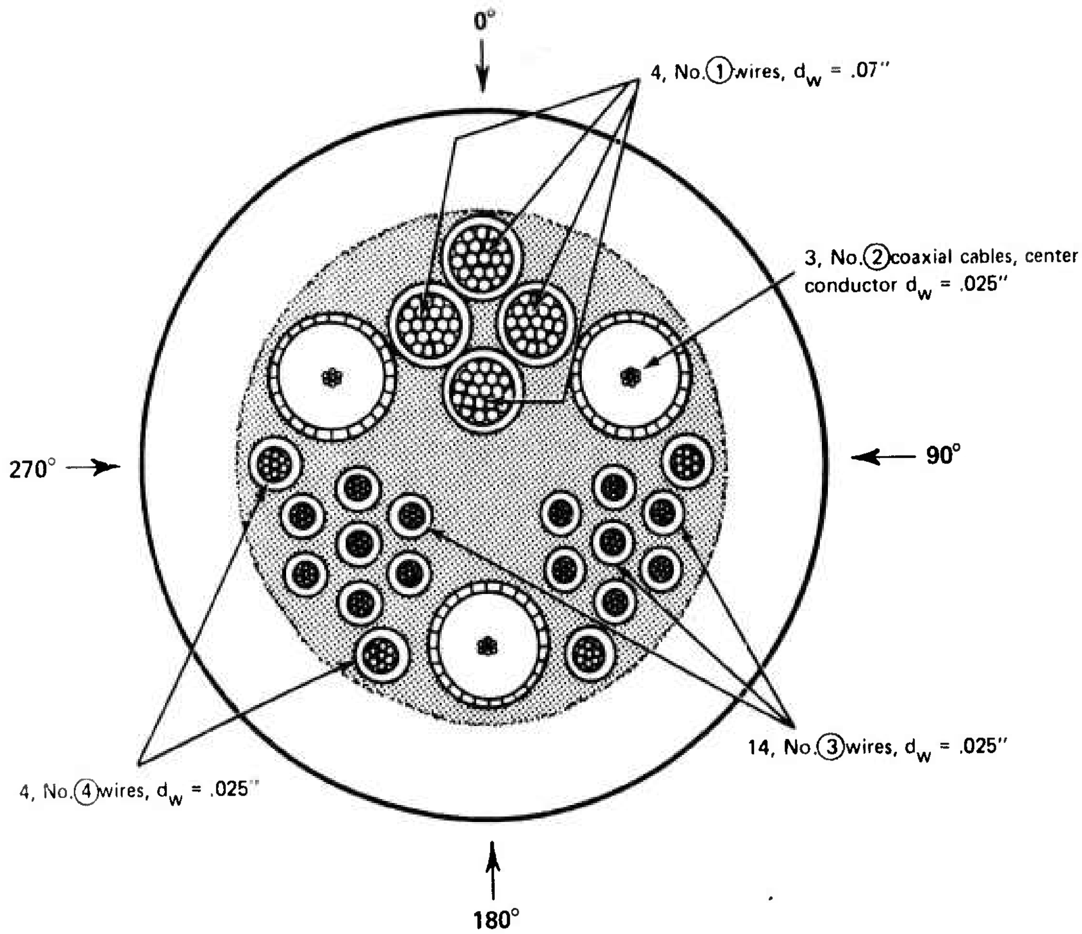

FIG. 2. Scale Drawing of Cross Section of Multiple Conductor Cable Used in Ballistic Tests.

TABLE 2. Results of Firing Program

Results of firing 17-grain fragments at 25 conductor (TV 25 TN) cable. Direction and wire notation refer to Figure 2.

Impact Velocity V-ft/sec	Description of Results
2020....	Direction, 0^{o} to 180^{o}. Fragment passed thru cable. Cut all four No. 1 wires. Cut left No. 2 coaxial cable. Cut bottom, left No. 4 wire. Cut bottom No. 2 coaxial cable. Cut two No. 3 wires in left bundle. 9 wires cut.
1330....	Direction, 20^{o} to 200^{o}. Fragment passed thru cable. Cut all four No. 1 wires. Cut right No. 2 coaxial cable. Cut three No. 3 wires in left bundle. Cut bottom left No. 4 wire. Cut bottom No. 2 coaxial cable. 10 wires cut.
810....	Direction, 0^{o}. Fragment stopped in top bundle of No. 1 wires. Three No. 1 wires cut. One No. 1 wire nicked and shorted out. 4 wires damaged.
905....	Direction, 0^{o} to 170^{o}. Fragment passed thru cable. Four No. 1 wires cut. One No. 3 wire cut in right bundle. Bottom No. 2 coaxial cable cut. Bottom right No. 4 wire cut. 7 wires cut.
445....	Direction, 310^{o} to 180^{o}. Fragment passed thru cable - did not go thru center. Cut left No. 2 coaxial cable. Cut one No. 1 wire. Cut two No. 3 wires in left bundle. Cut bottom No. 2 coaxial cable. 5 wires cut.
990....	Direction, 330^{o} to 150^{o}. Fragment passed thru cable. Cut top, left No. 2 coaxial cable. Cut one No. 1 wire. Cut one No. 3 wire in right bundle. 3 wires cut.
835....	Direction, 0^{o}. Fragment stuck in cable. Cut two No. 1 wires. Nicked two other No. 1 wires but not shorted out. 2 wires cut.
346....	Direction, 0^{o}. Fragment bounced back, did not stick in cable. Fragment did not break thru shielding. No damage.
725....	Direction, 320^{o} toward center. Fragment stuck in cable. Cut left No. 2 coaxial cable. Cut two No. 1 wires. Stopped in bundle of No. 1 wires. 3 wires cut.

SINGLE CONDUCTOR VULNERABILITY PREDICTION MODEL

Component vulnerability analyses include both "kill" criteria, given a hit on some specified portion of the presented area of a component, and a vulnerable area assignment for determining the probability of a hit on this specified portion of the presented area (given a hit on the component). Herein, a "kill" is defined as breaking (or shorting) a wire. Consideration is given first to wire breaking models for single solid and stranded conductors, and for coaxial cables. Vulnerable area models for single conductors are then considered.

BREAKING VELOCITY PREDICTION MODELS

Single conductors include solid or stranded wires. Coaxial cable is also considered as a single conductor herein. These three conductors will be considered in order.

Solid Conductor

During a previous research effort at the Denver Research Institute[1] a model was postulated for predicting the breaking velocity for solid conductor wires. This model was based upon the fact that when a fragment impacts a single wire, it must accelerate the wire mass in its path (suffering some deceleration in the process). Shear strain waves proceed outward in both directions accelerating the wire adjacent to that portion impacted. The shear strain in the wire is the ratio of the wire velocity (V_w) to the shear wave velocity (C_τ). Shear strain is accompanied by shear stress (τ). This shear stress creates a tensile stress (σ) which, because of its faster propagation velocity, propagates as a tensile strain wave out into the wire ahead of the shear wave. When either the shear strain or tensile strain exceeds some critical value the wire will fracture adjacent to the fragment and the strain waves cease to propagate. Thus, a critical transverse wire velocity exists; if exceeded, the wire breaks. Considering that a fragment will transfer momentum to the portion of wire directly in its path, inelastically, (accelerating the wire to some velocity less than the impact velocity) the breaking velocity will be related to the critical transverse velocity by:

$$V_{bw} = V_{ct} \left[1 + \frac{M_w}{M_p} \right] \qquad (1)$$

[1]Denver Research Institute. *A Function Description and the Functional Vulnerability of a Particular Radar(U)*, by Bruce D. Kautz and Rodney F. Recht. Denver, Colorado, DRI, January 1970. (DRI Technical Report No. 2528, publication CONFIDENTIAL.)

where

V_{ct} = the transverse critical velocity of the wire material

M_w = the weight of the wire accelerated by the fragment

M_p = the weight of the fragment

V_{bw} = the breaking velocity of the wire

The concept of breaking velocity is related to a transverse impact (normal to the wire axis). In order for an oblique impact to cause the wire to break, the velocity component normal to wire axis would have to be equal to V_{bw} as defined by Eq. 1. Thus, to define breaking velocity as a function of impact obliquity, the right side of Eq. 1 is multiplied by the secant of the obliquity angle.

Considering the accelerated wire segment to have a length, ℓ_w, and incorporating the obliquity function, Eq. 1 can be written,

$$V_{bw} = V_{ct}\left[1 + \frac{\pi\rho_w d_w^2 \ell_w}{4\ M_p}\right] \sec\theta \tag{2}$$

where

d_w = wire diameter

ρ_w = wire specific weight

θ = angle of obliquity

Any consistent set of units may be used.

For compact cylindrical fragments having lengths equal to their diameters, and assuming that the accelerated wire segment has a length equal to fragment diameter, Eq. 2 becomes

$$V_{bw} = V_{ct}\left[1 + \frac{(\pi/4)^{2/3}\ \rho_w d_w^2}{\rho_p^{\ 1/3}\ M_p^{\ 2/3}}\right] \sec\theta \tag{3}$$

where

ρ_p = fragment specific weight

In Reference 2, longitudinal critical velocities of soft copper wire are reported. These experimental values of the longitudinal critical velocity indicate that the transverse critical velocity for soft copper wires is near 400 ft/sec. This value is substantiated by the experiments in this study, as will be seen later. Using this value for (V_{ct}), the specific weights for copper (ρ_w) and steel (ρ_p), and defining the units of d_w and M_p as inches and grains, Eq. 3 reduces to

$$V_{bw} = 400 \left[1 + 157 \frac{d_w^2}{M_p^{2/3}} \right] \sec\theta \qquad (4)$$

Equation 4 does not correlate the experimental data obtained for solid conductor copper wires very well. Referring back to Eq. 2, it was assumed that the weight of wire accelerated by the fragment was equal to the weight of wire directly in the path of the fragment. This implies that the wire breaks immediately and that no strain waves propagate out into the wire when impacted at the critical transverse velocity. However, since the rupture strains have large plastic values, the lower valued elastic strains (which have a much higher propagation velocity) will propagate out into the wire beyond the zone impacted directly by the fragment. Evidence of this was noted during the course of the experimental firing program. A wire ballistically impacted near the breaking velocity characteristically exhibited severed ends bent back and rolled up into a fish hook shape. These considerations suggest redefining the segment length ℓ_w as being the product of the intercepted length and an empirical constant A (A being the ratio of the segment length to the intercepted length). From Eq. 2 it is obvious that this changes Eq. 4 to

$$V_{bw} = 400 \left[1 + \frac{157A\ d_w^2}{M_p^{2/3}} \right] \sec\theta \qquad (5)$$

Equation 5 was fitted to the data for solid copper conductors and 17-grain fragments. The following equation resulted:

$$V_{bw} = 400 \left[1 + \frac{385\ d_w^2}{M_p^{2/3}} \right] \sec\theta \qquad \text{(solid copper wire)} \qquad (6)$$

where the units of d_w and M_p are inches and grains, respectively.

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[2]J. C. Smith, C. A. Fenstermaker, and P. J. Shouse, "Behavior of Filamentous Materials Subjected to High Speed Tensile Impact", Dynamic Behavior of Materials, ASTM Materials Science Series-5, 1963. (ASTM Special Technical Publication No. 336.)

Figure 3 illustrates the correlation of this equation with the four data points. This figure also shows the agreement between the prediction curve of Eq. 6 for a 6-grain fragment and the data point for this size fragment and a wire of 0.102-inch diameter. The correlation between Eq. 6 and the data presented on Fig. 3 indicates that the involvement of the fragment weight and the wire diameter, as presented by Eq. 6, is of the correct nature. This equation should provide reliable predictions of the breaking velocity for solid, soft drawn copper conductor wire. For solid, drawn aluminum conductor wire, the following equation can be postulated based upon equations 1 and 6.

$$V_{bw} = 700 \left[1 + \frac{120\ d_w^2}{M_p^{\,2/3}} \right] \sec\theta \quad \text{(solid aluminum wires)} \quad (7)$$

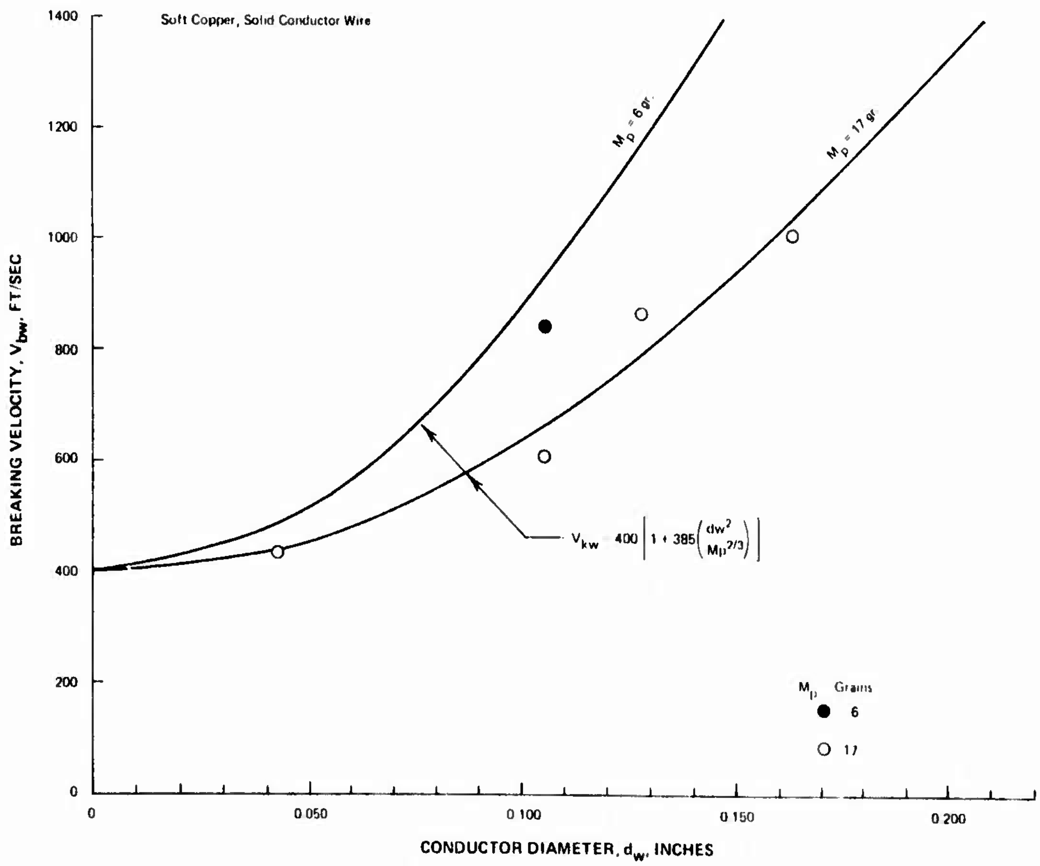

FIG. 3. Breaking Velocity as a Function of Conductor Diameter. Soft Copper, Solid Conductor Wire. Comparison of Prediction of Eq. 6 and Data.

Stranded Conductor

Many single conductor wires are made using multiple strands for the conductor. The tests against 16 gage, stranded conductor wire showed the breaking velocity to be lower than that for a similar diameter solid conductor wire (as predicted by Eq. 6). The data indicate that a lower critical transverse wave velocity is associated with the stranded conductor copper wire. This is explained by the fact that the individual strands of wire are not as free to move in the transverse direction (they are impeded by neighboring wires) and that (being twisted) they are not as taut as would be a solid conductor wire. Comparing the data for stranded copper conductor wire with an equation of the form of Eq. 6 indicates the critical transverse wave velocity for stranded copper wire should be reduced from 400 ft/sec to 320 ft/sec. This produces the equation:

$$V_{bw} = 320 \left[1 + \frac{385\ d_w^2}{M_p^{2/3}} \right] \sec\theta \quad \text{(stranded copper wire)} \qquad (8)$$

where

d_w is the overall diameter of the conductor, in.

Figure 4 shows the correlation of data for stranded copper wire with the predictions of Eq. 8. Using the apparent reduction in the critical transverse wave velocity of 0.8 for stranded wire, the following prediction equation can be postulated for stranded aluminum conductor wires:

$$V_{bw} = 560 \left[1 + \frac{120\ d_w^2}{M_p^{2/3}} \right] \sec\theta \quad \text{(stranded aluminum wire)} \qquad (9)$$

Coaxial Cable

The experimental data obtained for coaxial cable (see Table 1) shows that the breaking velocity of the stranded copper center conductor is higher (as would be expected) than is predicted by Eq. 8. An impacting fragment must penetrate through the outer covering, the braided shielding, and the thick insulator before impacting the center conductor. Comparing the experimental data with an equation of the form of Eq. 8 and assuming the V_{bw} to be a function of the insulator diameter, the following equation results:

$$V_{bw} = \left[320 + 1050\ d_I \right] \left[1 + \frac{385\ d_w^2}{M_p^{2/3}} \right] \sec\theta \text{ (coaxial cable)} \quad (10)$$

where

d_I is the diameter of the plastic insulator, inches (usually polyethylene)

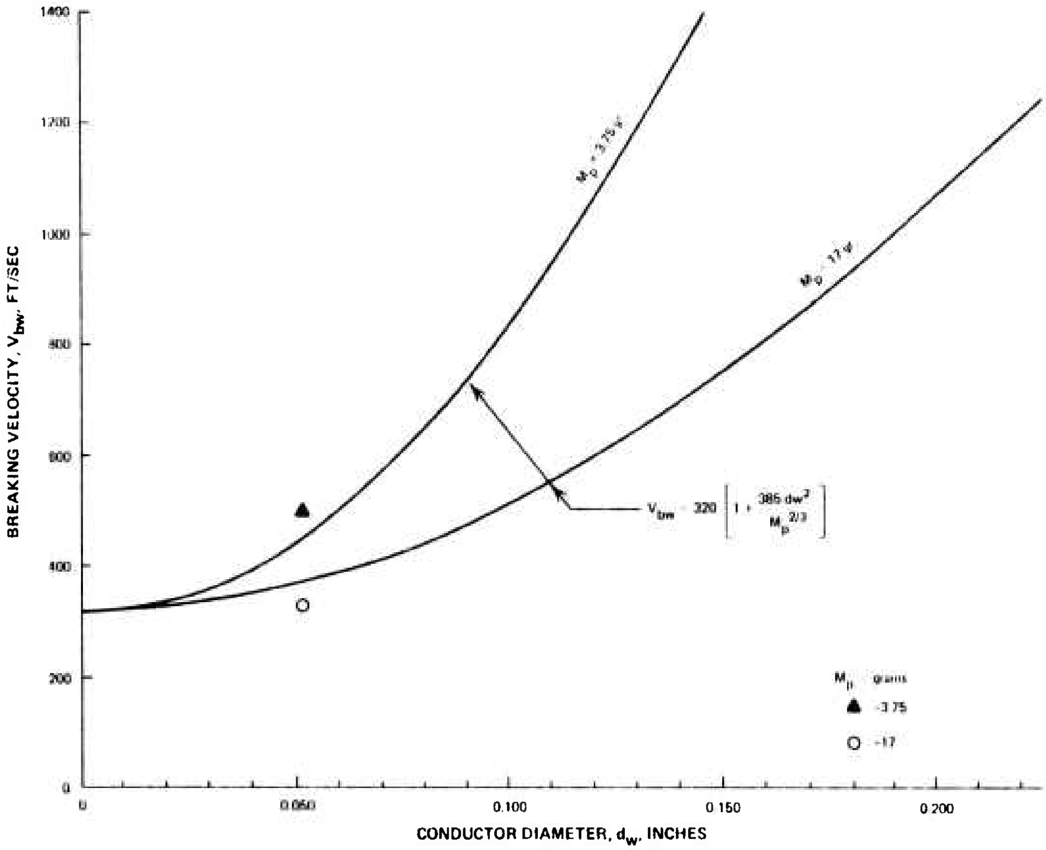

FIG. 4. Breaking Velocity as a Function of Conductor Overall Diameter. Soft Copper, Stranded Conductor Wire. Comparison of Predictions of Eq. 8 and Data.

For the RG 8/U coaxial cable, Eq. 10 predicts a breaking velocity of 985 ft/sec for the 6-grain cube (as compared to an experimental value of 1000 ft/sec). For the 17 grain fragment, the prediction is 805 ft/sec as compared to an 800 ft/sec experimental value. Eq. 10 should provide very reasonable predictions of the kill velocity for coaxial cables. The kill criterion is based upon severing the center conductor. As such, it is somewhat conservative since the possibility exists of shorting the conductor to the shielding at velocities less than V_{bw}. However, this shorting is dependent upon the fragment size and distance between the conductor and shielding (insulator thickness). As was discussed in *Results*, shorting was an occasional phenomena and did not occur at velocities much lower than the breaking velocity. The criterion represented by Eq. 10 is not, by any means, extremely conservative.

The foregoing has presented equations for the prediction of the breaking velocity pertaining to single conductor wires having solid copper conductors (Eq. 6), solid aluminum conductors (Eq. 7), stranded copper conductors (Eq. 8), stranded aluminum conductors (Eq. 9) and coaxial cable (Eq. 10).

VULNERABLE AREA DETERMINATIONS

Vulnerable area determinations for wires and cables involve considerations of fragment size. Breaking velocity determinations were based upon fragments whose mass centers passed very close to the wire axis. For modelling purposes it will be assumed that a direct hit occurs when the presented area of the fragment completely includes the wire diameter. Consider a cubical fragment having a dimension x. The weight (in grains) of such a fragment would be:

$$M_p = 7000\, \rho_p\, x^3 \tag{11}$$

or

$$x = \left[\frac{M_p}{7000\rho_p}\right]^{1/3} \tag{12}$$

Figure 5 illustrates how a wire having a diameter, d_w, can have an effective vulnerable diameter, d_v, which is greater than d_w. Using the geometry shown in Fig. 5, the following expression may be written for the vulnerable diameter, d_v, of such a single conductor wire:

$$d_v = x - d_w \tag{13}$$

Obviously, d_v, can never be less than d_w. Thus, when fragment size, x, becomes less than $2d_w$, then:

$$d_v = d_w \tag{14}$$

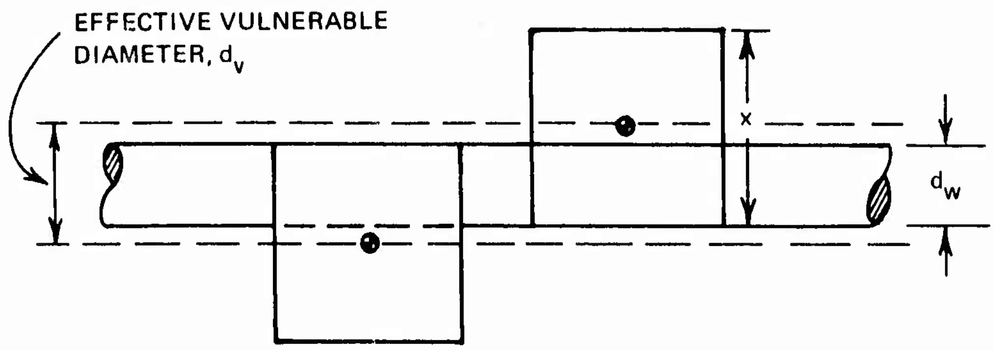

FIG. 5. Illustration of Relationship Between Fragment Size and Wire Diameter in Determining Wire Vulnerable Diameter.

The vulnerable area of a wire is its length times its vulnerable diameter times the cosine of the angle between the attack trajectory and the wire axis, θ. Using Eqs. 13 and 14, and the fragment size x as expressed by Eq. 12, the following definitions of the vulnerable area of single conductor wires and cables can be written:

If $x \leq 2d_w$, then

$$(A_v)_w = L_w\, d_w \cos\theta \tag{15}$$

If $x > 2d_w$, then

$$(A_v)_w = L_w\, (x - d_w) \cos\theta \tag{16}$$

where

$(A_v)_w$ = vulnerable area of wire

L_w = wire length

θ = angle between wire axis and attack aspect

d_w = conductor diameter

The vulnerability of single conductor wires to compact fragments can be accounted for in an analysis by assigning the wires a breaking velocity (as a function of fragment weight) as predicted by the appropriate equation (Eqs. 6, 7, 8, 9, or 10) and a vulnerable area as defined by Eqs. 15 and 16 (again a function of fragment weight). For fragments which are not compact, Eq. 2 must be used to determine breaking velocity, wherein ℓ_w may be defined as the product of the fragment width or diameter and the empirical constant, A, as in Eq. 5.

MULTIPLE CONDUCTOR CABLE VULNERABILITY MODEL

The recommended model for determining the vulnerability of multiple conductor cables is based upon the model for single conductor wires. Since multiple conductor cables are groups of single wires, the vulnerability of such a cable becomes the vulnerability of the single wires contained within. The impact behavior of a single wire contained within a cable differs from the behavior of an isolated wire in two ways. First, the single wire is usually protected by a cable covering and perhaps a braided shield. This will reduce the fragment velocity prior to impact of the interior conductors. Second, the single wires inside the cable will be supported and confined by neighboring wires. This confinement will reduce the ability of the wire to move transversely and absorb an impact. The effect of this confinement will be to reduce, somewhat, the breaking velocity of the wires. These two effects (protection by coverings and confinement of transverse motion) are opposite in their effect upon breaking velocities. It is felt justifiable to consider these factors offsetting and to consider single wires within a lightly shielded cable in the same manner as single wires. The procedures for doing this are dependent upon the type of multiple conductor cable being considered. This section will first consider cables comprised of single wires of the same type and size. Then cables containing a variety of wires will be considered.

MULTIPLE CONDUCTORS COMPRISED OF ONE WIRE TYPE AND SIZE

A multiple conductor containing wires all of the same type and size is considered to have the same damage criterion as one of the individual wires. The V_{bw} for one of these wires is determined by using the appropriate prediction equation. Since cable size is usually large in comparison to fragment size, the vulnerable area may be based upon overall equivalent diameter of the conductor envelope. The equivalent diameter may be represented by the average presented width of the conductor envelope considered from all radial directions. A vulnerability analyst may be confronted with the judgment that not all of the conductors within a cable are vital to the target function. In this case, the presented area should be multiplied by the square root of the ratio of the number of vital wires (N_v) to the number of wires (N) in the cable to obtain an estimate for vulnerable area. If vulnerable area is evaluated neglecting shielding by other wires, a somewhat larger vulnerable area would be predicted; hence the suggested procedure takes some account of such shielding. In summary, the vulnerable area of a multiple conductor cable containing identical conductors would simply be the product of the length, cosine of the attack angle, average diameter of the conductor envelope, and $(N_v/N)^{1/2}$.

MULTIPLE CONDUCTORS COMPRISED OF SEVERAL WIRE TYPES AND SIZES

The vulnerability representation of a multiple conductor cable containing different types of wires can be accomplished by developing a kill probability function for the cable. This is done by dividing the cable cross section into sectors which contain similar type and size wires. The breaking velocity is calculated for each wire by use of the appropriate equation (for the fragment weight of interest). Each sector becomes vulnerable to a given fragment when fragment velocity exceeds the breaking velocity of the representative wire. The kill probability (given a cable hit) for a given fragment weight increases when a sector becomes vulnerable by an amount equal to the ratio of the arc of the sector (in degrees) divided by 360 degrees. The probability of obtaining a cable hit is determined by the vulnerable area of the cable. This procedure is best explained by presenting an example of its use.

Consider the 25 conductor cable used in the experimental firing program. Figure 6 is a cross sectional drawing of this cable. The first step in the procedure is to divide the cable into sectors which can be represented by the same size and type of wire. Trajectories are considered as being directed toward the cable center. Figure 6 shows the cable divided in this manner. The sector labeled zone 1 represents four 13 gage (d_w = 0.07-inch) wires. A fragment impacting within this 75^o arc will encounter such a wire. These wires have a stranded copper conductor, therefore, Eq. 8 is used to predict the breaking velocity of these wires. Considering a 17-grain fragment, Eq. 8 predicts a breaking velocity of 410 ft/sec for this size wire. Three sectors represent the small coaxial cables within the cable. Equation 10 predicts a V_{bw} for these coaxial cables and a 17-grain fragment of 455 ft/sec. Zones 3 each represent 22 gage (d_w = 0.025 inch) wires. These wires also have stranded copper conductors. Equation 8 predicts a V_{bw} of 330 ft/sec for these wires against a 17-grain fragment. The wires with zones 3 represent the most vulnerable portion of the cable (lowest V_{bw}). The arcs (2 x 78^o) for these zones represent 156^o/360^o or 43% of the cable. At a velocity below the V_{bw} for these zones (330 ft/sec) a 17-grain fragment will not damage this multiple conductor cable. At 330 ft/sec, the kill probability, given a cable hit, becomes 0.43. At 410 ft/sec, the portion representing zone 1 (21%) is added, making the kill probability, 0.64. At 455 ft/sec, and above, the probability becomes 1.0 given a hit on the cable. Figure 7 presents the kill probability function as calculated for this test cable and a 17-grain fragment. While impact velocities normal to the cable axis have been considered here, obliquity simply increases the breaking velocities as indicated by the equations. This example illustrates how the single wire breaking velocity equations may be applied to the multiple conductor situation to develop a description of cable vulnerability. On Fig. 7, the kill probability function for 5 grain and 100 grain fragments are also presented. The probability functions presented on this figure show this particular multiple conductor cable to exhibit a probability function which varies from 0 to 1.0 over a rather narrow range of impact velocities. It also shows that a dramatic change in fragment weight (5 to 100 grains) does not produce a dramatic change in the velocities at which the kill probabilities become significant. A kill probability versus fragment weight and velocity plot, such as Fig. 7, will enable a vulnerability analyst to make a realistic representation of cables.

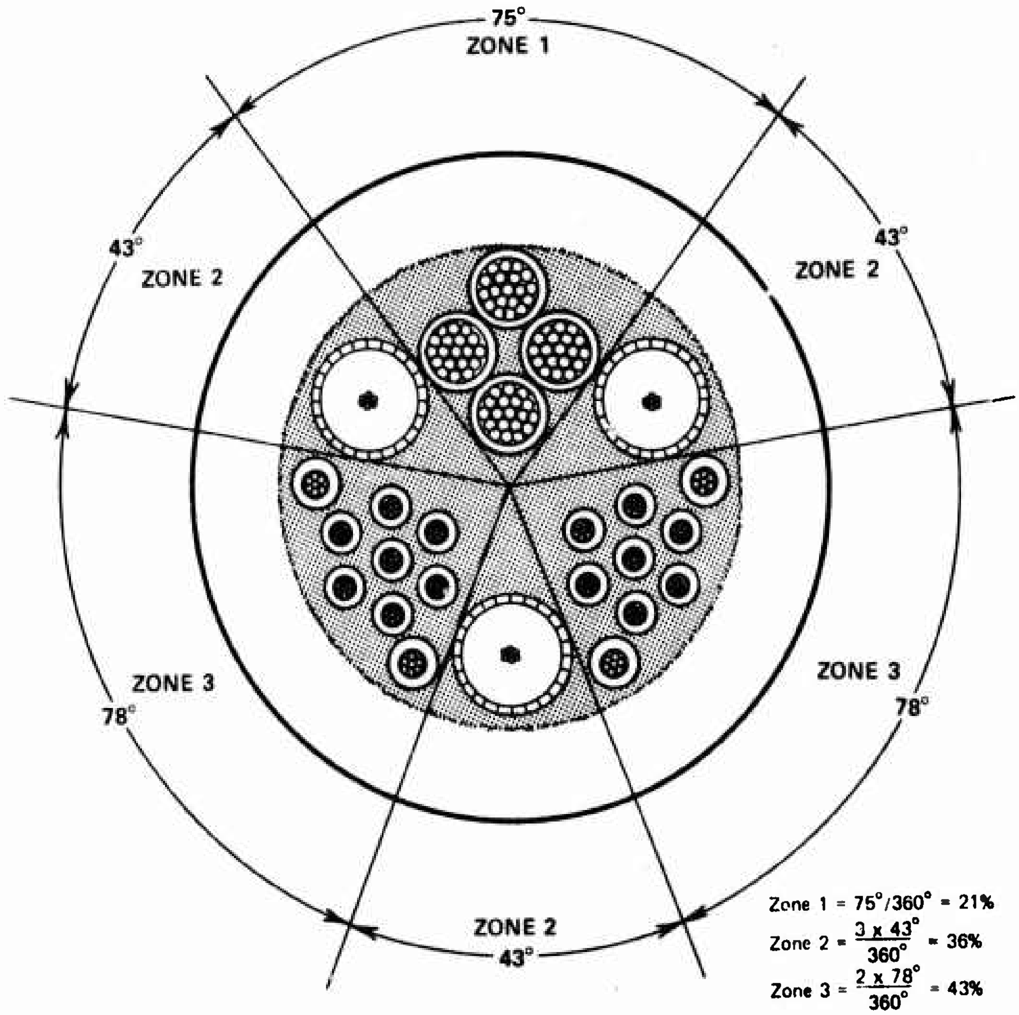

FIG. 6. Cross Section of a 25 Conductor Multiple Conductor Cable. Illustration of Division into Zones for Determining P_k Versus Fragment Velocity Functions.

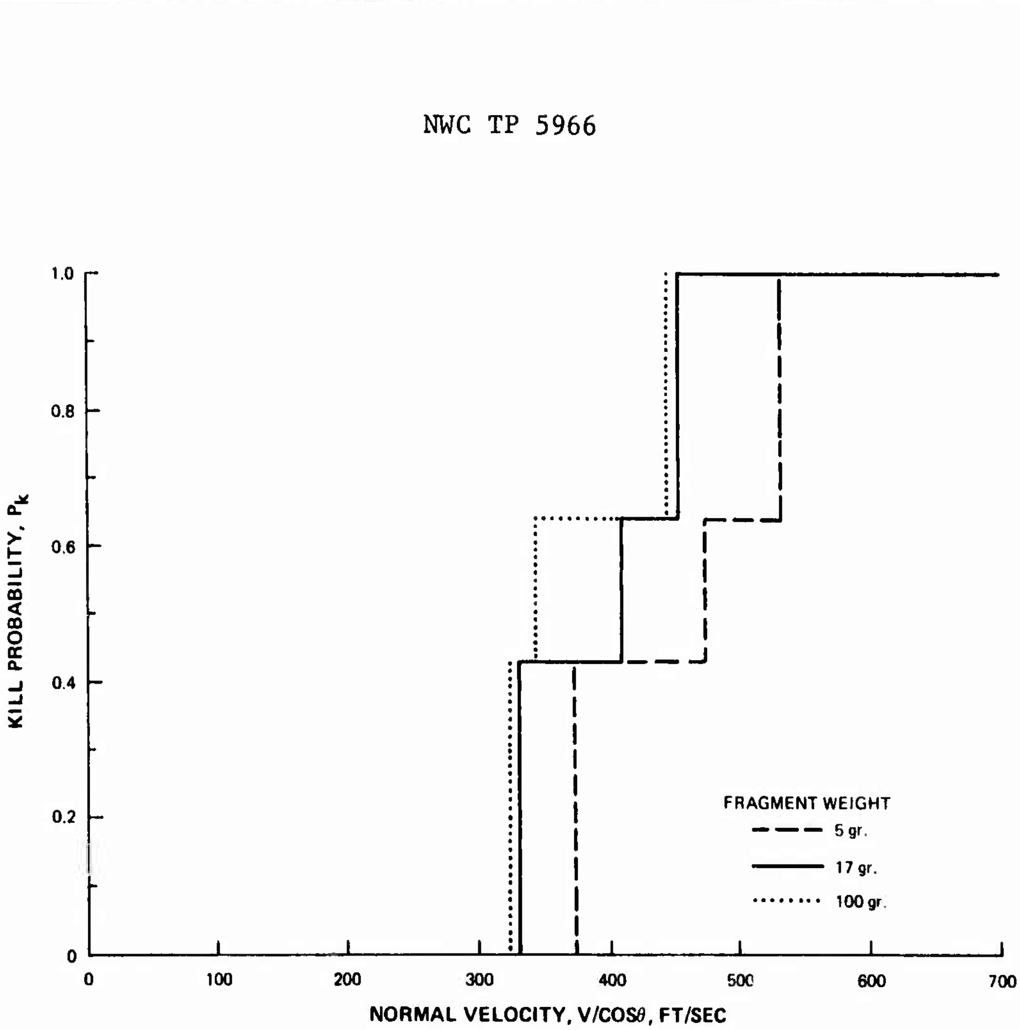

FIG. 7. Kill Probability Function Determined for a 25 Conductor Multiple Conductor Cable.

Referring to the test data listed in Table 2 and to Fig. 7, most of the data concerns tests at velocities well above predicted kill velocities. The fifth test listed in Table 2 pertains to an impact velocity of 445 ft/sec. The fragment cut one of the small coaxial cables (zone 2), cut one of the wires represented by zone 1, and two wires represented by zone 3. The fragment passed through the cable cutting all three types of wires represented by zones 1, 2, and 3. The plot on Fig. 7 shows that for the 17-grain fragment, an impact velocity of 445 ft/sec is slightly less than that required for $P_k = 1.0$ (455 fps); however, the prediction is reasonable as related to the observed damage. The eighth test in the series listed in Table 2 pertains to a test velocity of 346 ft/sec. The fragment impacted in zone 1. No damage was sustained by the cable. The prediction of the model for zone 1 was that a 17-grain fragment would require at least a 410 ft/sec velocity to cause damage in this zone. All other tests were at velocities above that predicted as producing a P_k of 1.0 and all of these tests did indeed functionally damage the cable.

The vulnerable area assigned to this type of multiple conductor cable is again the product of length, average diameter of the envelope enclosing the conductors, and the cosine of the attack angle. In this case, sectors containing non-vital wires possess kill probabilities of zero.

The models and methods described herein should provide the vulnerability analyst with tools for developing a very adequate vulnerability representation of wires and cables.

SUMMARY

Analytical equations, augmented with empirical constants have been developed which predict the breaking velocity, in terms of fragment weight, of various types and sizes of single conductor wires and cables. These equations, combined with definitions of vulnerable areas, provide a deterministic definition of the vulnerability of wires. Procedures have been developed for analyzing multiple conductor cables using the single conductor prediction equations to establish kill probability functions. These equations, models, and procedures should provide the vulnerability analyst with an accurate means of developing vulnerability representations for wires and cables.

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